Incongruent short words ending a sentence are a prerequisite for the elicitation of the auditory N400m

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1 Introduction

Speech communication, i.e. delivering and receiving auditory signals containing linguistic information, is an effective and important part of human interaction. Since speech processing and the underlying activation changes in cortical networks are known to happen extremely fast, speech processing is best studied with electro-magnetic brain imaging techniques such as EEG and MEG which have a temporal accuracy of a millisecond range [1]. An object of interest here is the processing by which the listener derives the semantic content embedded in the acoustic signal as well as the cortical areas involved in the process. These questions have often been studied with EEG using the N400-paradigm originally constructed for studies of reading comprehension [2].

Based on the numerous EEG studies both the visual and auditory N400 responses are thought to reflect modality-independent top-down processing that involves semantic memory functions (for a review, see [3]). In sentence-processing studies (as opposed to single-word studies) the N400 is elicited, for instance, in response to a word that does not fit the idea conveyed by the rest of the sentence [2,4].

Although the auditory and visual N400 responses are elicited in similar conditions [5-8], they have some differences the reasons of which have remained unresolved. Namely, the visual N400 seems to be of a shorter duration, which is reflected in the sharper form of the response in comparison to the broad auditory N400. This has been proposed to result from variable durations and recognition points of the target words [4,9,10] or from overlapping phonological and semantic processing [11]. In addition, since the individual responses have been of a somewhat shorter duration (sharper form) than the grand-averaged waveforms of subjects, it has also been suggested that the long duration of the auditory N400 response might be due to temporal differences of individual processing strategies [12]. The possible contribution of stimulus duration *per se* on the auditory N400 has also been mentioned [10]. It seems, then, that despite the excellent temporal resolution provided by MEG and EEG, the temporal smearing underlying the generation of the auditory N400(m) remains to be established.

In addition to this temporal smearing, the location(s) of the cortical networks underlying the generation of the N400 are still unknown. A few studies on the visual N400m have been conducted using MEG [13-15] although at present, to our knowledge, there are no published reports on the auditory magnetic N400m response. We have recently conducted several experiments for eliciting an N400m response which could reliably be located by single current dipole estimation. As a starting point, we used stimuli very similar to those of previous EEG experiments, i.e. words of long, slightly variable durations. However, source localisation of the resulting response by dipole estimation turned out to be impossible. By systematically modifying the details of the experimental set-up we studied the prerequisites of the reliable elicitation of the auditory N400m in MEG.

2 Methods

2.1 Subjects

The subjects were normal-hearing, right-handed adults either fluent in (N = 16, age 23-33 years) or with no knowledge of Finnish (N = 5, age 22-31 years). The subjects provided informed consent and the experiment was approved by the Ethical Committee of Helsinki University Central Hospital.

2.2 Materials

The stimuli consisted of 480 different sentences that ended either with a probable or an improbable noun of either long or short duration. The sentences were thus divided into four groups of 120 sentences according to the sentence-ending word that was:

1. A congruent long-duration final word:
   I would like to have a ***sandwich****.*
2. An incongruent long-duration final word:
   My aunt is knitting a* ***computer**.*

3. A congruent short-duration final word:
   I always drink coffee from a ***cup****.*
4. An incongruent short-duration final word:
   At a dentist you open your* ***cup**.*

The sentences were first recorded using a DAT-recorder (DAT 44 Daz, microphone SM 10A) and then transferred onto a computer. Each sentence was produced at a normal speech rate by a female speaker in a sound-attenuated room. Careful measures were taken in order to avoid distorting the coarticulation and giving the listener false cues which might affect the ERPs: all sentences were produced as a whole instead of, for example, transposing a separately produced final word to the end of the sentence. The target words were then triggered from the point where the last phoneme of the preceding word changed towards the first phoneme of the target word and was thus affected by coarticulation. This was accomplished by careful monitoring of the signal and the use of an oscillogram.

2.3 Procedure

The stimuli, divided into four sequences containing the same number of each sentence type, presented in pseudo-random order (not more than 3 sentences of the same class followed each other) and lasting 12 minutes each, were delivered to the subjects binaurally through plastic tubes and ear pieces. The sound pressure level of the presentation was approximately 65 dB SPL. The subject's task was to listen carefully and to press a response pad each time the meaning of the sentence sounded odd. In order to make sure that even non-Finnish speaking subjects listened attentively they were instructed to search for possibly familiar items (*e.g.* "Helsinki") in the stimulation.

2.4 Recordings

Cortical activity was measured simultaneously with a 122-channel magnetometer (Neuromag Ltd.) and five EEG electrodes (Fpz, Fz, Cz, Pz, Cz) placed on the scalp using the 10/20-system and referenced to linked mastoids. Horizontal and vertical eye movements and blinks were recorded and epochs during which the EOG magnitude exceeded 150 µV were discarded from the data. A minimum of 100 epochs per sentence type were averaged time-locked to the sentence-ending word (pass-band filtering 1-20 Hz). Source localisation was performed using equivalent current dipoles (ECDs).

3 Results

3.1 The Finnish-speaking subjects

As illustrated in Figure 1 the magnetic (1a) and electric (1b) responses were very similar. The long-duration incongruent words evoked a low-amplitude response that seemed to be scattered in time and had no clearly observable peak. Locating this response by ECDs was not possible. In contrast, the short-duration incongruent word evoked a strong response peaking at around 420 ms in both hemispheres.

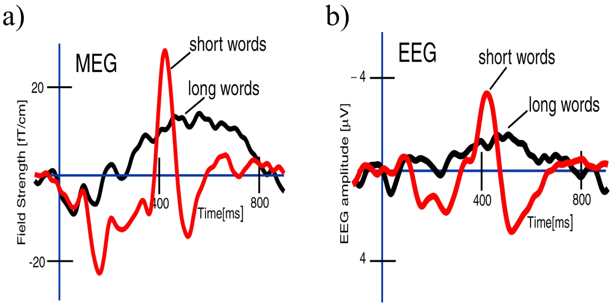

Figure 1*: Grand averaged MEG (a) and EEG (b) waveforms of Finnish subjects. The short-duration improbable word evoked a response peaking at around 420 ms (depicted in red). Long-duration words evoked the responses depicted in black.*

Source localisation of the EMF elicited by the short-duration incongruent word was straightforward and reliable: the average goodness-of-fit of the dipole was 82.5 % in the left and 83.6% in the right hemisphere (Figure 2). Although inter-individual differences were observed, the ECD localisation suggested a generator mechanism in the vicinity of the auditory cortex.

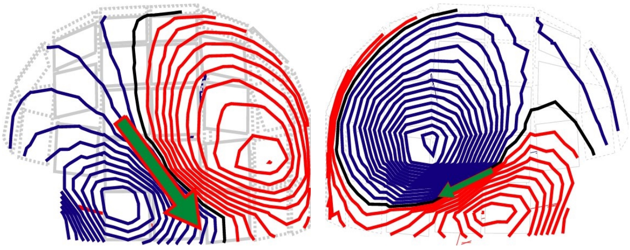

Figure 2: *Dipoles of a single representative subject fitted at 420 ms from the onset of the short improbable word. Because of the strength and short duration of the elicited response the dipole fitting was reliable: the average goodness of fit of all subjects was 82.5% on the left and 83.6% on the right hemisphere.*

3.2 The non-Finnish-speaking subjects

Neither the short- nor the long-duration words evoked a response at around 400 ms in the non-Finnish-speaking subjects (Figures 3a and 3b). This occurred despite all the subjects noticing the repeated occurrence of the short-duration sentence-ending word. This was indicated by their response-key press after each occurrence of the ending word.

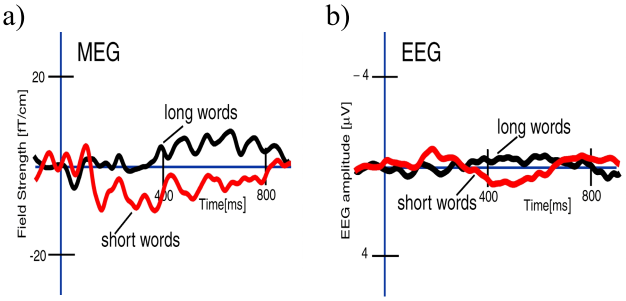

Figure 3: *Grand-averaged MEG (a) and EEG (b) waveforms of non-Finnish-speaking subjects. Neither the short- nor the long-duration words evoked a response at around 400 ms.*

4 Discussion

To our knowledge, the are no published reports on the magnetic counterpart of the auditory N400 to date. Based on our present observations, one reason for this lack of data on N400m might be that the duration of the stimulus words has been overlooked. We found it impossible to locate the source of the response elicited by the long-duration words. On the contrary, estimating the source of the response elicited by short-duration words was reliable and straightforward.

Our data therefore suggests that the short duration of the stimulus word is an important prerequisite for source localisation of the auditory N400m. Stimulus duration might even determine the extent to which we can benefit from the excellent temporal resolution of both EEG and MEG: on the one hand, short-duration words seem to elicit a response the peak latency of which can easily be defined. On the other, long-duration words evoke a response the peak latency of which is difficult to define or it has to be defined by mathematical operations.

Furthermore, the broad auditory N400 observed in previous EEG-measurements has been suggested to reflect 1) overlapping phonological and semantic processing, 2) variable recognition points of the target words or 3) temporal processing differences between subjects. However, based on the present observations as well as data from an experiment (Mäkelä et al., in preparation) where only one incongruent sentence-ending long-duration word was used (and the variation in stimulus-duration was thus eliminated), we suggest that this broad form of the N400(m) might be due to the long duration of the target words (see [16,17]).

Since the responses elicited by the long-duration words were not identical in the Finnish and non-Finnish-speaking subjects (which could be expected if the response was a purely physiological reaction to a long-duration acoustic signal), it is possible that the long-duration responses also reflect aspects of lexical processing. Then again, since the short-duration word did not evoke a response in the non-Finnish-speaking subjects even though they recognised the phonetic pattern of the word, it is unlikely that the response observed in Finnish subjects would be an "offset"-response reflecting a merely physiological process caused by the ending of the stimulus.

In conclusion, we propose that the elicitation of the response observed in Finnish subjects requires recognition of the semantic content embedded in the acoustic pattern and that this response is very likely the auditory N400m, the magnetic counterpart of the electric auditory N400. Whether this response reflects the combining of the content and form or semantic processing only will be addressed elsewhere (Tiitinen et al., in preparation, Mäkelä et al. in preparation). At present, we note that in future studies of the N400(m) utilising auditory stimuli, close attention should be paid to the stimulus duration *per se*.

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